Low-Density Universe

Evidence has gradually accumulated that the universe has less matter, and therefore is expanding faster, than the theory of inflation traditionally predicts. But a more sophisticated version of the theory readily explains the observations

by Martin A. Bucher and David N. Spergel

Cosmology has a reputation as a difficult science, but in many ways explaining the whole universe is easier than understanding a single-celled animal. On the largest cosmic scales, where stars, galaxies and even galaxy clusters are mere flecks, matter is spread out evenly. And it is governed by only one force, gravity. These two basic observations—large-scale uniformity and the dominance of gravity—are the basis of the big bang theory, according to which our universe has been expanding for the past 12 billion years or so. Despite its simple underpinnings, the theory is remarkably successful in explaining the velocity of galaxies away from one another, the relative amounts of light elements, the dim microwave glow in the sky and the general evolution of astronomical structures. The unfolding of the cosmos, it seems, is almost completely insensitive to the details of its contents. Unfortunately for biologists, the same principle does not apply to even the simplest organism.

Yet there are paradoxes inherent in the big bang theory. Two decades ago cosmologists resolved these troubling inconsistencies by incorporating ideas from particle physics—giving rise to the theory of "inflation." But now this elaboration is itself facing a crisis, brought on by recent observations that contradict its prediction for the average density of matter in the cosmos. Cosmologists are realizing that the universe may not be quite so simple as they had thought. Either they must posit the existence of an exotic form of matter or energy, or they must add a layer of complexity to the theory of inflation. In this article we will focus on the second option.

Strictly speaking, the big bang theory does not describe the birth of the universe, but rather its growth and maturation. According to the theory, the infant universe was an extremely hot, dense cauldron of radiation. A part of it, a chunk smaller than a turnip, eventually enlarged into the universe observable today. (There are other parts of the universe, perhaps infinite in extent, that we cannot see, because their light has not yet had time to reach the earth.) The idea of an expanding universe can be confusing; even Albert Einstein initially regarded it with suspicion. When the cosmos expands, the distance between any two independent objects increases. Distant galaxies move apart because the space between them is getting larger of its own accord, just as raisins move apart in a rising loaf of bread.

A natural consequence of the expansion of a uniform universe is Hubble's law, whereby galaxies are moving away from the earth (or from any other point in the universe) at speeds proportional to their distance. Not all objects in the universe obey this law, because mutual gravitational attraction fights against the swelling of space. For example, the sun and the earth are not moving apart. But it holds on the largest scales. In the simplest version of the big bang, the expansion has always proceeded at much the same rate.

In the Beginning, Paradox

As the youthful universe expanded, it cooled, thinned out and became increasingly complex. Some of the radiation condensed into the familiar elementary particles and simple atomic nuclei. Within roughly 300,000 years, the temperature had dropped to 3,000 degrees Celsius, cool enough for the electrons and protons to combine and form hydrogen atoms. At this moment the universe became transparent, setting loose the famous cosmic microwave background radiation. The radiation is very smooth, indicating that the density of matter in different regions of the early universe varied by only one part in 100,000. Tiny though these differences were, the slight concentrations eventually grew into galaxies and galaxy clusters

BUBBLE UNIVERSES are self-contained universes that grow within a larger and otherwise empty "multiverse." True to the weirdness of relativity, time and space have different meanings inside and outside each bubble; time, as perceived inside, increases toward the center of the bubble; the wall of the bubble represents the big bang for that universe. Of course, this painting depicts an impossible perspective. Even if an observer could exist outside the bubble, he or she or it could not peer inside, because the bubble expands at the speed of light. Such ideas may sound like science fiction, but so does any other cutting-edge science.

ALFRED T. KAMAJIAN

[see "The Evolution of the Universe," by P. James E. Peebles, David N. Schramm, Edwin L. Turner and Richard G. Kron; Scientific American, October 1994].

Despite its successes, the standard big bang theory cannot answer several profound questions. First, why is the universe so uniform? Two regions on opposite sides of the sky look broadly the same, yet they are separated by more than 24 billion light-years. Light has been traveling for only about 12 billion years, so the regions have yet to see each other. There has never been enough time for matter, heat or light to flow between them and homogenize their density and temperature [*see illustration on page 69*]. Somehow the uniformity of the universe must have predated the expansion, but the theory does not explain how.

Conversely, why did the early universe have any density variations at all? Fortunately, it did: without these tiny undulations, the universe today would still be of uniform density—a few atoms per cubic meter—and neither the Milky Way nor the earth would exist.

Finally, why is the rate of cosmic expansion just enough to counteract the collective gravity of all the matter in the universe? Any significant deviation from perfect balance would have magnified itself over time. If the expansion rate had been too large, the universe today would seem nearly devoid of matter. If gravity had been too strong, the universe would have already collapsed in a big crunch, and you would not be reading this article.

Cosmologists express this question in terms of the variable omega, Ω, the ratio of gravitational energy to kinetic energy (that is, the energy contained in the motion of matter as space expands). The variable is proportional to the density of matter in the universe—a higher density means stronger gravity, hence a larger Ω. If Ω equals one, its value never changes; otherwise it rapidly decreases or increases in a self-reinforcing process, as either kinetic or gravitational energy comes to dominate. After billions of years, Ω should effectively be either zero or infinity. Because the current density of the universe is (thankfully) neither zero nor infinity, the original value of Ω must have been exactly one or extraordinarily close to it (within one part in 10^{18}). Why? The big bang theory offers no explanation apart from dumb luck.

These shortcomings do not invalidate the theory—which neatly explains billions of years of cosmic history—but they do indicate that it is incomplete. To fill in the gap, in the early 1980s cosmologists Alan H. Guth, Katsuhiko Sato, Andrei D. Linde, Andreas Albrecht and Paul J. Steinhardt developed the theory of inflation [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; Scientific American, May 1984].

The price paid for resolving the paradoxes is to make big bang theory more complicated. The inflationary theory postulates that the baby universe went through a period of very rapid expansion (hence the name). Unlike conventional big bang expansion, which decelerates over time, the inflationary expansion accelerated. It pushed any two independent objects apart at an ever increasing clip—eventually faster than light. This motion did not violate relativity, which prohibits bodies of finite mass from moving through space faster than light. The objects, in fact, stood still relative to the space around them. It was space itself that came to expand faster than light.

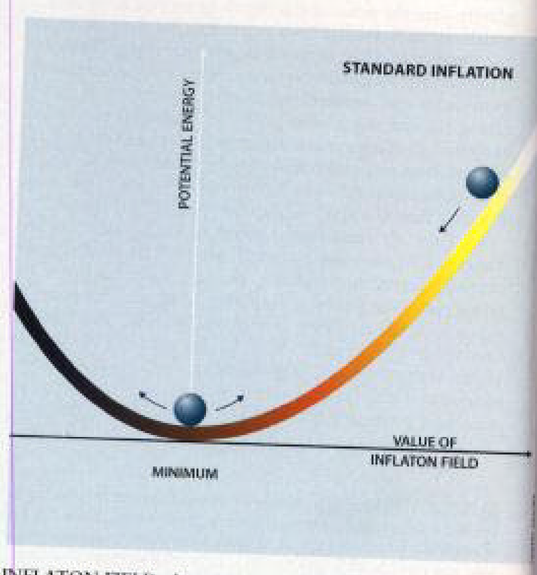
Such rapid expansion early on explains the uniformity of the universe seen today. All parts of the visible universe were once so close together that they were able to attain a common density and temperature. During inflation, different parts of this uniform universe fell out of touch; only later, after inflation ended, did light have time to catch up with the slower, big bang expansion. If there is any nonuniformity in the broader universe, it has yet to come into view.

Fieldwork

To bring about the rapid expansion, inflationary theory adds a new element to cosmology, drawn from particle physics: the "inflaton" field. In modern physics, elementary particles, such as protons and electrons, are represented by quantum fields, which resemble the familiar electric, magnetic and gravitational fields. A field is simply a function of space and time whose oscillations are interpreted as particles. Fields are responsible for the transmission of forces.

The inflaton field imparts an "antigravity" force that stretches space. Associated with a given value of the inflaton field is a potential energy. Much like a ball rolling down a hill, the inflaton field tries to roll toward the bottom of its potential [*see illustration below*]. But the expansion of the universe introduces what may be described as a cosmological friction, impeding the descent. As long as the friction dominates, the inflaton field is almost stuck in place. Its value is nearly constant, so the antigravity force gains in strength relative to gravity—causing the distance between once nearby objects to increase at ever faster rates. Eventually the field weakens and converts its remaining energy into radiation. Afterward the expansion of the universe continues as in the standard big bang.

Cosmologists visualize this process in terms of the shape of the universe. According to Einstein's general theory of rela-

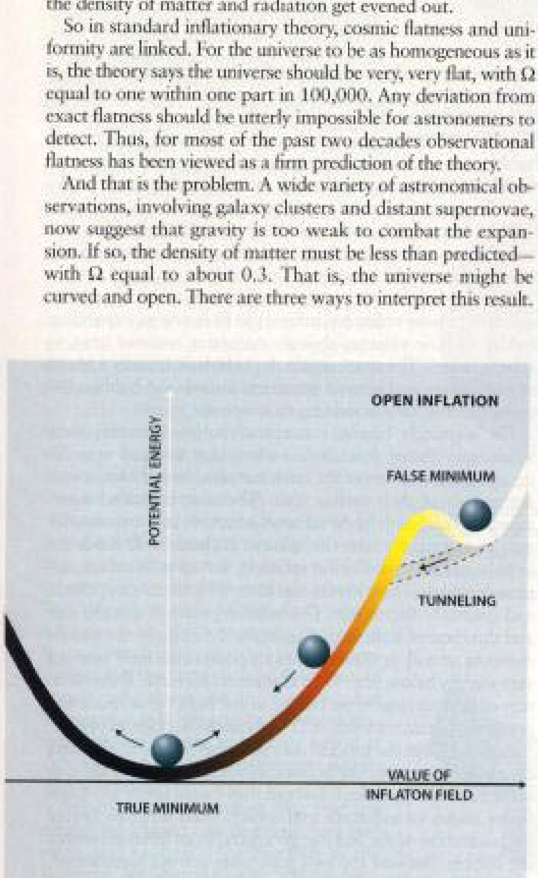


INFLATON FIELD, the origin of the force that caused space to expand, behaved like a ball rolling down a hill: it sought to minimize its potential energy (*vertical axis*) by changing its value (*horizontal axis*). The field began high up the hill because of quantum processes at the dawn of time. In standard inflation (*left*), the field then rolled straight to its lowest value. But in open inflation (*right*), it got caught in a tivity, gravity is a geometric effect: matter and energy warp the fabric of space and time, distorting the paths that objects follow. The overall expansion of the universe, which itself is a kind of bending of space and time, is controlled by the value of Ω [*see box on page 67*]. If Ω is greater than one, the universe has a positive curvature, like the surface of an orange but in three spatial dimensions (the spherical, or "closed," geometry). If Ω is less than one, the universe has a negative curvature, like a potato chip (the hyperbolic, or "open," geometry). If it equals one, the universe is flat, like a pancake (the usual Euclidean geometry).

Inflation flattens the observable universe. Whatever the initial shape of the universe, the rapid expansion bloats it to colossal size and pushes most of it out of sight. The small visible fraction might seem flat, just as a small part of the earth's surface seems flat. Inflation thus pushes the observed value of Ω toward one. At the same time, any initial irregularities in the density of matter and radiation get evened out.

So in standard inflationary theory, cosmic flatness and uniformity are linked. For the universe to be as homogeneous as it is, the theory says the universe should be very, very flat, with Ω equal to one within one part in 100,000. Any deviation from exact flatness should be utterly impossible for astronomers to detect. Thus, for most of the past two decades observational flatness has been viewed as a firm prediction of the theory.

And that is the problem. A wide variety of astronomical observations, involving galaxy clusters and distant supernovae, now suggest that gravity is too weak to combat the expansion. If so, the density of matter must be less than predicted—with Ω equal to about 0.3. That is, the universe might be curved and open. There are three ways to interpret this result.



valley, or "false minimum." Throughout most of the universe it stayed there, and inflation never ended. In a few lucky regions, the field "tunneled" out of its valley and completed its descent. One such region became the bubble in which we live. In both styles of inflation, once the field approached its final resting place, it sloshed back and forth, filling space with matter and radiation. The big bang had begun.

The first is that inflationary theory is completely wrong. But if cosmologists abandon inflation, the formidable paradoxes so nicely resolved by the theory would reappear, and a new theory would be required. No such alternative is known.

A second interpretation takes heart from the accelerating expansion inferred from the observations of distant supernovae [see "Surveying Space-time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff, on page 46]. Such expansion hints at additional energy in the form of a "cosmological constant." This extra energy would act as a weird kind of matter, bending space much as ordinary matter does. The combined effect would be to flatten space, in which case the inflationary theory has nothing to worry about [see "Cosmological Antigravity," by Lawrence M. Krauss, on page 52]. But the inference of the cosmological constant is plagued by uncertainties about dust and the nature of the stars that undergo supernova explosions. So cosmologists are keeping their options open (so to speak).

Bubble Universes

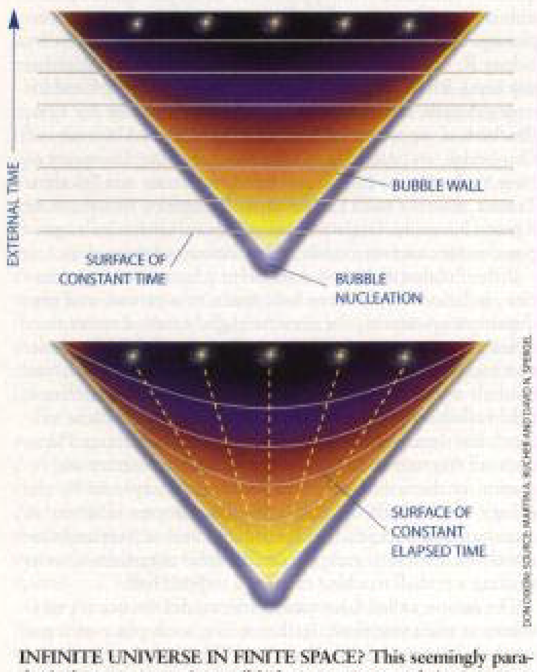
A third path is to take the observations at face value and ask whether a flat universe really is an inevitable consequence of inflation. This approach involves yet another extension of the theory to still earlier times, with some new complexity. The route was first mapped in the early 1980s by Sidney R. Coleman and Frank de Luccia of Harvard University and J. Richard Gott III of Princeton University. Ignored for over a decade, the ideas were recently developed by one of us (Bucher), along with Neil G. Turok, now at the University of Cambridge, and Alfred S. Goldhaber of the State University of New York at Stony Brook, and by Misao Sasaki and Takahiro Tanaka, now at Osaka University, and Kazuhiro Yamamoto of Kyoto University. Linde and his collaborators have also proposed some concrete models and extensions of these ideas.

If the inflaton field had a different potential-energy function, inflation would have bent space in a precise and predictable way—leaving the universe slightly curved rather than exactly flat. In particular, suppose the potential-energy function had two valleys—a false (local) minimum as well as a true (global) minimum [*see illustration at left*]. As the inflaton field rolled down, the universe expanded and became uniform. But then the field got stuck in the false minimum. Physicists call this state the "false vacuum," and any matter and radiation in the cosmos were almost entirely replaced by the energy of the inflaton field. The fluctuations inherent in quantum mechanics caused the inflaton field to jitter and ultimately enabled it to escape from the false minimum—just as shaking a pinball machine can free a trapped ball.

The escape, called false-vacuum decay, did not occur everywhere at the same time. Rather it first took place at some random location and then spread. The process was analogous to bringing water to a boil. Water heated to its boiling point does not instantaneously turn into steam everywhere. First, because of the random motion of atoms, scattered bubbles nucleate throughout the liquid—rather like the burbling of a pot of soup. Bubbles smaller than a certain minimum size collapse because of surface tension. But in larger bubbles, the energy difference between the steam and the superheated water overcomes surface tension; these bubbles expand at the speed of sound in water.

In false-vacuum decay, quantum fluctuations played the role of the random atomic motion, causing bubbles of true vacuum to nucleate. Surface tension destroyed most of the bubbles, but a few managed to grow so large that quantum effects became unimportant. With nothing to oppose them, their radius continued to increase at the speed of light. As the outside wall of a bubble passed through a point in space, the inflaton field at that point was jolted out of the false minimum and resumed its downward descent. Thereafter the space inside the bubble inflated much as in standard inflationary theory. The interior of this bubble corresponds to our universe. The moment that the inflaton field broke out of its false minimum corresponds to the big bang in older theories.

For points at different distances from the center of nucleation, the big bang occurred at different times. This disparity seems strange, to say the least. But careful examination of the inflaton field reveals what went on. The inflaton acted as a chronometer: its value at a given point represented the time elapsed since the big bang occurred at that point. Because of the time lag in the commencement of the big bang, the value of the inflaton was not the same everywhere; it was highest at the wall of the bubble and fell steadily toward the center. Mathematically, the value of the inflaton was constant on surfaces with the shape of hyperbolas [*see illustration below*].



INFINITE UNIVERSE IN FINITE SPACE? This seemingly paradoxical arrangement is possible because space and time are perceived differently outside (*top*) and inside (*bottom*) the bubble universe. Here, time—as seen by exterior observers—marches upward. Space, by definition, is any line or surface that connects points at a certain time (*horizontal lines*). The bubble looks finite. Interior observers, however, are aware only of elapsed time, the amount that has passed since the bubble first arrived at a given position. As elapsed time increases, temperature decreases—which impels physical change (*hot is yellow; cool is black*). Surfaces of constant elapsed time are hyperbolas, which bend upward and never touch the bubble wall. Points inside move apart because of cosmic expansion (*dotted lines*). Thus we count ourselves kings of infinite space.

The value of the inflaton is no mere abstraction. It determined the basic properties of the universe inside the bubble—namely, its average density and the temperature of the cosmic background radiation (today 2.7 degrees C above absolute zero). Along a hyperbolic surface, the density, temperature and elapsed time were constant. These surfaces are what observers inside the bubble perceive as constant "time." It is not the same as time experienced outside the bubble.

How is it possible for something so fundamental as time to be different on the inside and on the outside? Based on the understanding of space and time before Einstein's theories of relativity, such a feat would indeed have seemed impossible. But in relativity, the distinction between space and time blurs. What any observer calls "space" and "time" is largely a matter of convenience. Loosely speaking, time represents the direction in which things change, and change inside the bubble is driven by the inflaton.

Bounded in a Nutshell

According to relativity, the universe has four dimensions—three for space, one for time. Once the direction of time is determined, the three remaining directions must be spatial; they are the directions in which time is constant. Therefore, a bubble universe seems hyperbolic from the inside. For us, to travel out in space is, in effect, to move along a hyperbola. To look backward in time is to look toward the wall of the bubble. In principle, we could look outside the bubble and before the big bang, but in practice, the dense, opaque early universe blocks the view.

This melding of space and time allows an entire hyperbolic universe (whose volume is infinite) to fit inside an expanding bubble (whose volume, though increasing without limit, is always finite). The space inside the bubble is actually a blend of both space and time as perceived outside the bubble. Because external time is infinite, so is internal space.

The seemingly bizarre concept of bubble universes frees inflationary theory from its insistence that Ω equal one. Although the formation of the bubble created hyperbolas, it said nothing about their precise scale. The scale is instead determined by the details of the inflaton potential, and it varies over time in accordance with the value of Ω. Initially, Ω inside the bubble equals zero. During inflation, its value increases, approaching one. Thus, hyperbolas start off with an abrupt bend and gradually flatten out. The inflaton potential sets the rate and duration of flattening. Eventually inflation in the bubble comes to an end, at which point Ω is poised extremely near but very slightly below one. Then Ω starts to decrease. If the duration of inflation inside the bubble is just right (to within a few percent), the current value of Ω will match the observed value.

At first glance the process may seem baroque, but the main conclusion is simple: the uniformity and geometry of the universe need not be linked. Instead they could result from different stages of inflation: uniformity, from inflation before the nucleation of the bubble; geometry, from inflation within the bubble. Because the two properties are not intertwined, the need for uniformity does not determine the duration of inflation, which lasts just long enough to give the hyperbolas the desired degree of flatness.

In fact, this formulation is a straightforward extension of the big bang theory. The standard view of inflation describes what happened just before the conventional big bang expansion. The new conception, known as open inflationary theory,

The Geometry of the Universe

If the universe had an "outside" and people could view it from that perspective, cosmology would be much easier. Lacking these gifts, astronomers must infer the basic shape of the universe from its geometric properties. Everyday experience indicates that space is Euclidean, or "flat," on small scales. Parallel lines never meet, triangles span 180 degrees, the circumference of a circle is $2\pi r$, and so on. But it would be wrong to assume that the universe is Euclidean on large scales, just as it would be wrong to conclude that the earth is flat just because a small patch of it looks flat.

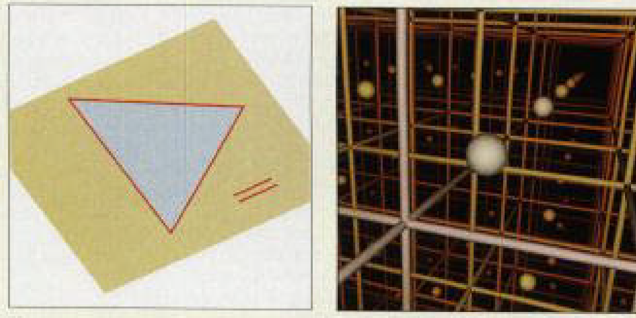
There are two other possible three-dimensional geometries consistent with the observations of cosmic homogeneity (the equivalence of all points in space) and isotropy (the equivalence of all directions). They are the spherical, or "closed," geometry and the hyperbolic, or "open," geometry. Both are characterized by a curvature length analogous to the earth's radius. If the curvature is positive, the geometry is spherical; if negative, hyperbolic. For distances much smaller than this length, all geometries look Euclidean.

In a spherical universe, as on the earth's surface, parallel lines eventually meet, triangles can span up to 540 degrees, and the circumference of a circle is smaller than $2\pi r$. Because the space curves back on itself, the spherical universe is finite. In a hyperbolic universe, parallel lines diverge, triangles have less than 180 degrees, and the circumference of a circle is larger than $2\pi r$. Such a universe, like Euclidean space, is infinite in size. (There are ways to make hyperbolic and flat universes finite, but they do not affect the conclusions of inflationary theory.)

These three geometries have quite different effects on perspective (*right*), which distort the appearance of features in the cosmic microwave background radiation. The largest ripples in the background have the same absolute size regardless of the specific process of inflation. If the universe is flat, the largest undulations would appear to be about one degree across. But if the universe is hyperbolic, the same features should appear to be only half that size, simply because of geometric distortion of light rays.

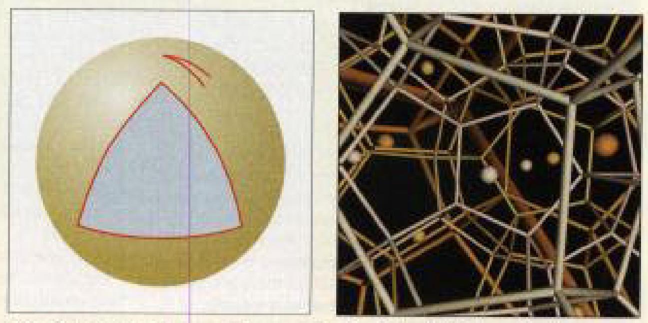
Preliminary observations hint that the ripples are indeed one degree across [see News and Analysis, "The Flip Side of the Universe," by George Musser; SCIENTIFIC AMERICAN, September 1998]. If confirmed, these results imply that the open inflationary theory is wrong. But tentative findings are often proved wrong, so astronomers await upcoming satellite observations for a definitive answer. —*M.A.B. and D.N.S.*

THREE GEOMETRIES are shown here from two different perspectives: a hypothetical outside view that ignores, for the sake of illustration, one of the spatial dimensions (*left column*) and an inside view that shows all three dimensions as well as a reference framework (*right column*). The outside view is useful for seeing the basic geometric rules. The inside view reveals the apparent sizes of objects (which, in these diagrams, are the same actual size) at different distances. Here objects and framework redden with distance.

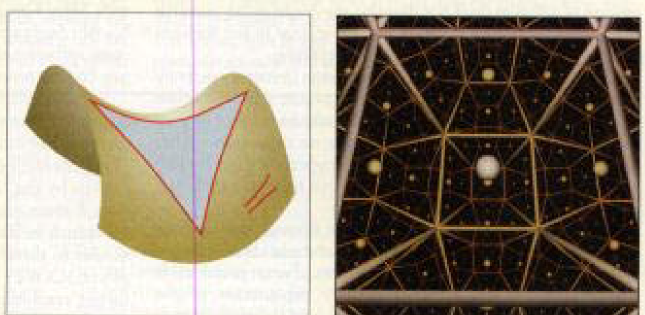


STUART LEVY National Center for Supercomputing Applications AND TAMARA MUNZNER Stanford University

Flat space obeys the familiar rules of Euclidean geometry. The angular size of identical spheres is inversely proportional to distance—the usual vanishing-point perspective taught in art class.



Spherical space has the geometric properties of a globe. With increasing distance, the spheres at first seem smaller. They reach a minimum apparent size and subsequently look larger. (Similarly, lines of longitude emanating from a pole separate, reach a maximum separation at the equator and then refocus onto the opposite pole.) This framework consists of dodecahedra.



Hyperbolic space has the geometry of a saddle. Angular size shrinks much more rapidly with distance than in Euclidean space. Because angles are more acute, five cubelike objects fit around each edge, rather than only four.

How Did the Universe Begin?

The laws of physics generally describe how a physical system develops from some initial state. But any theory that explains how the universe began must involve a radically different kind of law, one that explains the initial state itself. If normal laws are road maps telling you how to get from A to B, the new laws must justify why you started at A to begin with. Many creative possibilities have been proposed.

In 1983 James B. Hartle of the University of California at Santa Barbara and Stephen W. Hawking of the University of Cambridge applied quantum mechanics to the universe as a whole, producing a cosmic wave function analogous to the wave function for atoms and elementary particles. The wave function determines the initial conditions of the universe. According to this approach, the usual distinction between future and past breaks down in the very early universe; the time direction takes on the properties of a spatial direction. Just as there is no edge to space, there is no identifiable beginning to time. In an alternative hypothesis, Alexander Vilenkin of Tufts University proposed a "tunneling" wave function determined by the relative probabilities for a universe of zero size to become a universe of finite size of its own accord.

Last year Hawking and Neil G. Turok, also at Cambridge, suggested the spontaneous creation of an open inflationary bubble from nothingness. This new version of open inflation bypasses the need for false-vacuum decay, but Vilenkin and Andrei D. Linde of Stanford University have challenged the assumptions in the calculation.

Linde has tried to skirt the problem of initial conditions by speculating that inflation is a process without beginning [see "The Self-Reproducing Inflationary Universe," by Andrei Linde; SCIENTIFIC AMERICAN, November 1994]. In the classical picture, inflation comes to an end as the inflaton field rolls down its potential. But because of quantum fluctuations, the field can jump up the potential as well as down. Thus, there are always regions of the universe—in fact, constituting a majority of its volume—that are inflating. They surround pockets of space where inflation has ended and a stable universe has unfolded. Each pocket has a different set of physical constants; we live in the one whose constants are suited for our existence. The rest of the universe carries on inflating and always has. But Vilenkin and Arvind Borde, also at Tufts, have argued that even this extension of inflation does not describe the origin of the universe completely. Although inflation can be eternal in the forward time direction, it requires an ultimate beginning.

J. Richard Gott III and Li-Xin Li of Princeton University recently proposed that the universe is trapped in a cyclic state, rather like a time traveler who goes back in time and becomes her own mother. Such a person has no family tree; no explanation of her provenance is possible. In Gott and Li's hypothesis, our bubble broke off from the cyclic proto-universe; it is no longer cyclic but instead is always expanding and cooling.

Unfortunately, it may be very difficult (though perhaps not impossible) for astronomers to test any of these ideas. Inflation erases almost all observational signatures of what preceded it. Many physicists suspect that a fuller explanation of the preinflationary universe—and of the origin of the physical laws themselves—will have to await a truly fundamental theory of physics, perhaps string theory. —*M.A.B. and D.N.S.*

adds another stage preceding standard inflation. Another theory describing even earlier times will be needed to explain the original creation of the universe [*see box at left*].

Life in a bubble universe has a number of interesting consequences (not to mention possibilities for science-fiction plots). For instance, an alien observer could safely pass from the outside to the inside of the bubble. But once inside, the observer (like us) could never leave, for doing so would require traveling faster than light. Another implication is that our universe is only one of an infinity of bubbles immersed in a vast, frothy sea of eternally expanding false vacuum. What if two bubbles collided? Their meeting would unleash an explosion of cosmic proportions, destroying everything inside the bubbles near the point of impact. Fortunately, because the nucleation of bubbles is an extremely rare process, such cataclysms are improbable. Even if one occurred, a substantial portion of the bubbles would not be affected. To observers inside the bubbles but at a safe distance, the event would look like a broiling-hot region in the sky.

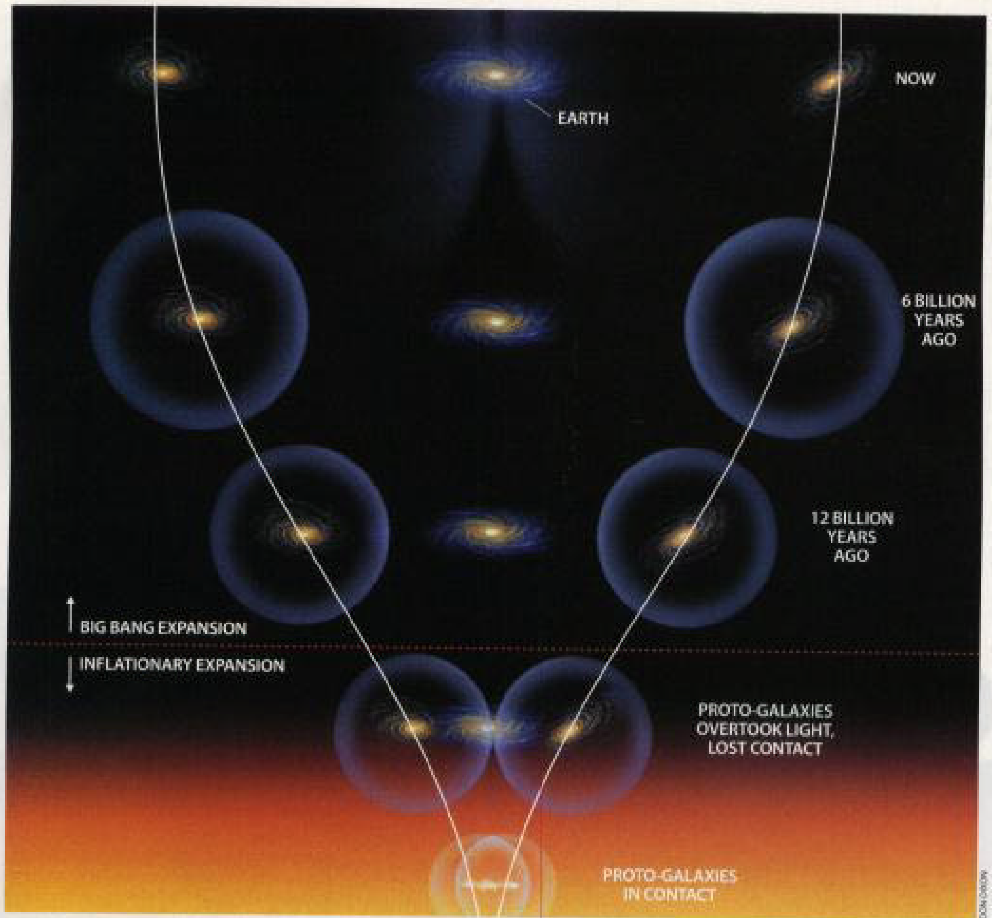
Corroborating Evidence

How does one test this theory? To explain why the universe is uniform is certainly a good thing. But validating a theory requires that some quantitative predictions be compared with observations. The specific effects of open inflation were calculated in 1994 with contributions by the two groups that refined the theory, as well as Bharat V. Ratra and P. James E. Peebles of Princeton.

Both the old and the new concepts of inflation make definite forecasts based on quantum effects, which caused different points in space to undergo slightly different amounts of inflation. When inflation ended, some energy was left over in the inflaton field and became ordinary radiation—the fuel of the subsequent big bang expansion. Because the duration of inflation varied from place to place, so did the amount of residual energy and therefore the density of the radiation.

The cosmic background radiation provides a snapshot of these undulations. In open inflation, it is affected not only by fluctuations that develop within the universe but also by ones that arise outside the bubble and propagate inside. Other ripples are set in motion by imperfections in the nucleation of the bubble. These patterns ought to be most notable on the largest scales. In effect, they allow us to look outside our bubble universe. In addition, one of us (Spergel), working with Marc Kamionkowski, now at Columbia University, and Naoshi Sugiyama of the University of Tokyo, realized that open inflation should have other, purely geometric effects [*see box on preceding page*].

At the current level of precision, the observations cannot distinguish between the predictions of the two inflationary theories. The moment of truth will come with the planned deployment late next year of the Microwave Anisotropy Probe (MAP) by the National Aeronautics and Space Administration. A more advanced European counterpart, Planck, is due for launch in 2007. These satellites will perform observations similar to those of the Cosmic Microwave Background Explorer (COBE) satellite nearly a decade ago, but at much higher resolution. They should be able to pick out which theory—either the cosmological constant or open inflation—is correct. Or it could well turn out that neither fits, in which case researchers will have to start over and find some new ideas for what happened in the very early universe. ■



MAJOR PARADOX in cosmology is the near uniformity of the universe. In the normal big bang expansion, such regularity is impossible (*upper part of diagram*). Billions of years ago two galaxies on opposite sides of the sky began to shine. Although the universe was expanding, the light was able to overtake other galaxies and finally reach us in the Milky Way. Humans, viewing the galaxies through telescopes, remarked that they looked much the same. Yet light from either galaxy had not yet arrived at the other. How, without seeing each other, could the two have harmonized their appearance? Inflation (*lower part*) provides an answer. In the first split second of cosmic history, the predecessors of the galaxies were touching. Then the universe expanded at an accelerating rate, pulling them apart at faster than the speed of light. Ever since, the galaxies have been unable to see each other. When inflation ended, light began to overtake them again; after billions of years, the galaxies will come back into contact.

The Authors

MARTIN A. BUCHER and DAVID N. SPERGEL study the physics of the very early universe. Bucher, currently in the department of applied mathematics and theoretical physics at the University of Cambridge, is one of the pioneers of open inflationary theory. Spergel is professor in the department of astrophysical sciences at Princeton University. The father of two young children, Julian and Sarah, he is a member of the science team for the Microwave Anisotropy Probe, a satellite designed to map the cosmic microwave background with high resolution. Both authors also work on such matters as galaxy formation and structure and defects in the fabric of space and time.

Further Reading

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Additional information on the Microwave Anisotropy Probe and Planck satellite can be found at map.gsfc.nasa.gov/ and astro.estec.esa.nl/SA-general/Projects/Planck/ on the World Wide Web.